ISOCHRONOUS MODE OF THE FUTURE COLLECTOR RING AT THE CENTRE FOR HEAVY ION RESEARCH, DARMSTADT, GERMANY

by

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Short-lived exotic nuclei can be produced and separated with the high-energy nuclear beam facility called fragment separator at the Centre for Heavy Ion Research. These nuclides can be injected and stored in the storage ring called experimental storage ring. The lower lifetime limit of the presently existing methods for mass measurements on these nuclides at the experimental storage ring is about a few seconds. We have developed and investigated an isochronous operational mode of the future collector ring, that makes mass measurements feasible for nuclides with lifetimes down to a few microseconds. A mass resolving power of about 150 000 is expected.

Key words: exotic nuclei, lifetime, storage ring, collector ring

INTRODUCTION

The nuclear mass is a fundamental nuclear property. It is essential for our understanding of nuclear structure. While the mass in general is well known for nuclei close to β-stability, the masses of a large number of exotic nuclei near the proton and neutron drip-lines have not been measured yet. Such nuclei are characterized by low production cross-sections and short half-lives. Hence the measured techniques must be fast and highly efficient. A storage ring tuned in the isochronous mode, proposed by Wollnik [1], can be used for such measurements. First mass measurements of exotic nuclei using an isochronous ring showed that a mass resolving power of about 150000 could be achieved [2, 3].

Construction of a new accelerator facility is planed at GSI Institute – Facility for Antiproton and Ion Research (FAIR [4]) for production a variety of new short-lived nuclides by using projectile fragmentation or uranium fission reactions. The new collector ring (CR) [5] is planned to be constructed, where one of the functions is devoted to operation at isochronous condition. This condition is special for mass measurements.

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Theory

The stored ions circulate in the ring with a revolution frequency f, which is determined by the particle velocity v and the length C of the corresponding orbit

$$f \quad \frac{v}{C} \tag{1}$$

The path length C is determined by the magnetic rigidity [6]

$$B\rho \quad \frac{\gamma m v}{q} \tag{2}$$

where m and q denote the particle rest mass and electric charge, respectively, while γ is the relativistic Lorentz factor.

For a reference particle the magnetic rigidity and path length are $(B\rho)_0$ and C_0, respectively, and the relation between $(B\rho)$, C and $(B\rho)_0$ and C_0 is

$$\frac{\mathrm{d}C}{C_0} \quad \frac{1}{\gamma_t^2}\frac{\mathrm{d}(B\rho)}{(B\rho)_0} \tag{3}$$

The transition point γ_t is an ion-optical quantity that describes the detour, which particles of an increased magnetic rigidity with respect to $(B\rho)_0$ have to go in the bending magnets due to the dispersion D

$$\frac{1}{\gamma_t^2} \quad \frac{1}{C}\oint\frac{D(s)}{\rho}\mathrm{d}s \tag{4}$$

Here, s denotes the co-ordinate along the reference orbit in the storage ring while ρ is the radius of curvature of this reference orbit in the bending sections. The integration is carried out over one turn.

Combining eqs. (1)-(3) one finds the explicit dependence of f on the mass-to-charge ratio m/q and the velocity v of the ions under consideration

$$\frac{\mathrm{d}f}{f} \quad \frac{1}{\gamma_t^2}\frac{\mathrm{d}\frac{m}{q}}{\frac{m}{q}} \quad 1 \quad \frac{\gamma^2}{\gamma_\tau^2}\frac{\mathrm{d}v}{v} \tag{5}$$

For exotic nuclei the velocity distribution

$$\frac{\mathrm{d}v}{v} \quad \frac{1}{\gamma^2}\frac{\mathrm{d}p}{p} \tag{6}$$

corresponds to a momentum width of $\mathrm{d}p/p =$ 1% [7] and, therefore, in general the last term in eq. (5) is a severe limitation for precise mass measurements. Only if this term can be reduced to a negligible value, the revolution frequency becomes a direct measure for the mass-to-charge ratio. There are two ways to fulfill this condition:

(1) in Schottky mass spectrometry (SMS) electron cooling [1, 8] is used in order to obtain an identical mean velocity with a narrow distribution for all ions. In case of low beam intensities the velocity spread can be reduced to $\Delta v/v$ $^{-}$ [9] at the storage ring, resulting in a mass resolving power of about $m/\Delta m$ = 650000 [10]. The cooling process requires at least some seconds, hence, SMS is limited to nuclei with half-lives of more than a few seconds, and

(2) in isochronous mass spectrometry (IMS) the velocity dependence is overcome by choosing the ion-optical mode of the storage ring and the beam energy such that the velocity difference between two particles of the same species is counterbalanced by the corresponding change of the orbit length C. Hence, the revolution frequency becomes velocity independent. In terms of synchrotron theory this isochronicity is expressed by the fulfillment of the isochronicity condition

$$\gamma = \gamma_{\mathrm{t}} \tag{7}$$

Here, no electron cooling is needed and the necessary condition for mass measurement is achieved immediately after injection of the particles. Thus, this method is particularly well-suited for exotic nuclei with lifetimes SMS shorter than the time required for SMS.

FUTURE COLLECTOR RING

In spite that isochronous mode and IMS method have been developed at the existing experimental storage ring (ESR) at GSI, the ESR was not designed to be an isochronous ring. Therefore, its isochronous mode has some disadvantages which are taken into account and will be eliminated in the future collector ring (CR). The improvements of the CR compared to ESR are:

- the CR optics have been selected especially to operate in the isochronous mode in first and higher orders,
- the transverse and momentum acceptance will be larger than in the ESR,
- three injection septum magnets will be installed instead of one in the ESR. Also, three full-aperture kickers instead of one half-aperture kicker as used in the ESR, and
- the CR will be achromatic at its straight sections, which is advantageous and improves the isochronicity in addition. The achromatism will also lead to a better time-of-flight (TOF) resolution, since the TOF detectors will be installed in one of straight section.

The CR is a planned storage ring with fourfold symmetry with two arcs and two straight sections. A total circumference of CR is 213.65 meters. The CR consists of 24 identical 15° sector magnets and 12 magnetic quadrupole families (48 quadrupoles in total) to achieve first order focusing condition. For the correction of second order aberrations 6 magnetic hexapole families (24 hexapoles in total) will be installed. The layout of the CR is shown in fig. 1.

Transition energy requirement

The aim of the IMS in the CR is to measure masses of a large region of short-lived exotic nuclei.

The maximum value for magnetic rigidity, $B\rho_{\mathrm{max}}$ = 13 Tm, limits the particle energy to values corresponding to γ = 2.32 for neutron deficient nuclei (m/q) and γ = 1.66 for very neutron rich nuclides (m/q). Therefore, the isochronous condition, see eq. (8), can be fulfilled only by a significant reduction of the value of γ_{t}. For example, for γ_{t} = 1.84 (keeping the maximum magnetic rigidity) it is possible to measure of mass-to-charge ratios only up to m/q = 2.71. To expand the mass region it is necessary to reduce the transition energy further, while keeping the maximum magnetic rigidity. In this paper, the features of the isochronous mode for the setting γ_{t} = 1.67 which allow the measurements of mass-to-charge ratios up to m/q = 2.71, are described.

RESULTS

First order calculation

First-order calculations of the isochronous settings have been done by the computer code GICOSY [11].

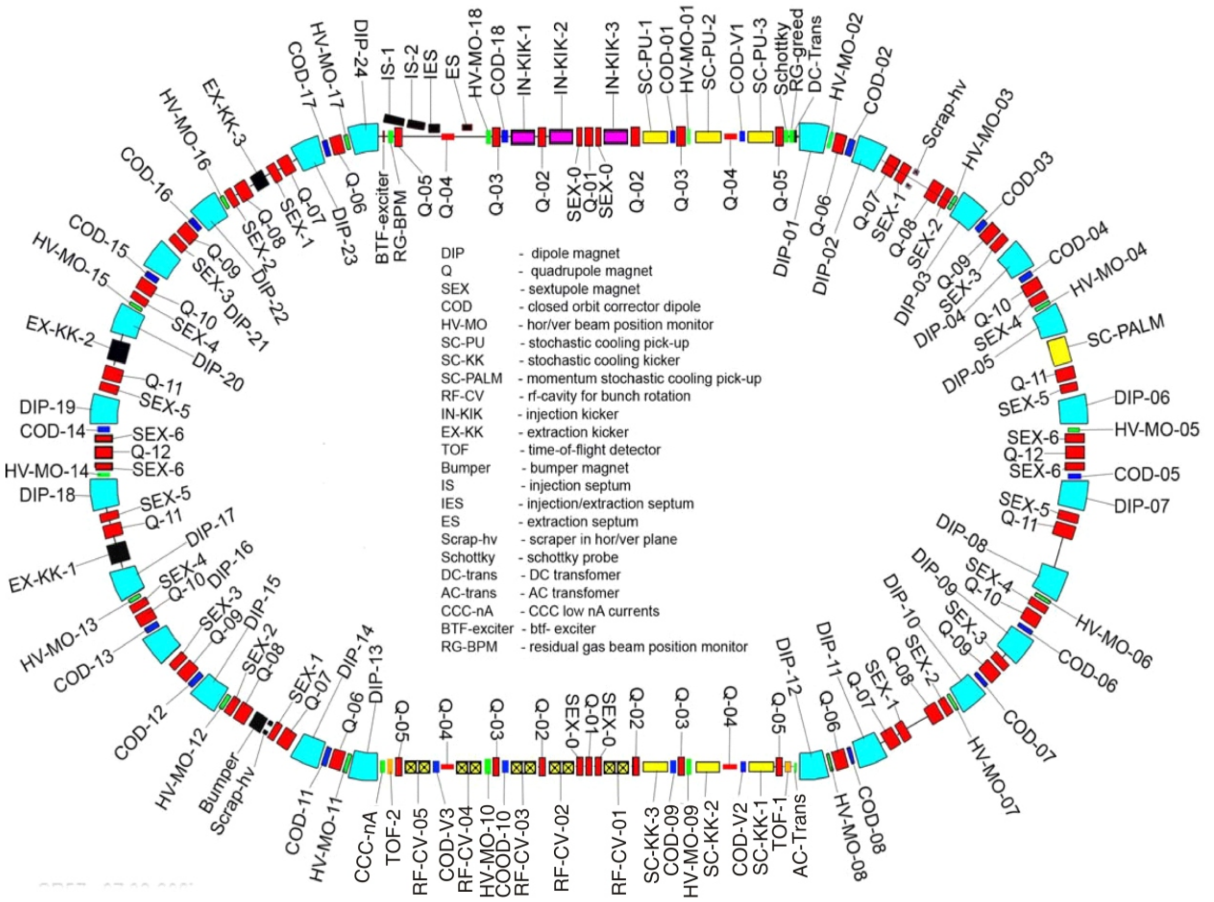

Figure 1. The layout of the CR with major installations

Usually the starting point of an ion optical lattice calculation is chosen at a symmetric point where the phase space ellipses are assumed upright, *i. e.* Twiss parameter [6] α_T in both x and y planes are zero; *i. e.* $\alpha_x = \alpha_y = 0$. In case of the CR, the symmetric point has been chosen in the middle of the Q-01 quadrupole (see fig. 1).

All twelve quadrupole families have been tuned in a way to keep the beam inside the magnet apertures and to fulfill the following requirements.

– *Isochronous condition*

$$\gamma = \gamma_t \tag{8}$$

– *Twiss parameter periodicity [6]*

$$\alpha_B(s + L_0) = \alpha_B(s) \tag{9a}$$

$$\beta_B(s + L_0) = \beta_B(s) \tag{9b}$$

$$\gamma_B(s + L_0) = \gamma_B(s) \tag{9c}$$

where α_B, β_B, and γ_B are the Twiss parameters [6], s is the path length along the reference path and L_0 is the circumference of the ring lattice.

– *Dispersion function periodicity and achromatism [6]*

$$D(s + L_0) = D(s) \tag{10a}$$

$$D'(s + L_0) = D'(s) \tag{10b}$$

$$\int_0^s h(\tilde{s})C(\tilde{s})\mathrm{d}\tilde{s} = 0 \tag{10c}$$

$$\int_0^s h(\tilde{s})S(\tilde{s})\mathrm{d}\tilde{s} = 0 \tag{10d}$$

where $h = 1/\rho$ is the bending power of the bending sections, D' – the derivatives of the dispersion function with respect to variable s, and C and S are "cos like" and "sin like" solutions of the homogeneous differential equation [6].

– *Stability criterion [6, 12]*

$$|\cos\mu| = \left|\frac{1}{2}Tr\,[M(s + L_0)]\right| < 1 \tag{11}$$

where μ is the phase advance function [6, 12] and M – the first order transport matrix at the position $s + L_0$.

– *Beam size*

At the TOF deflector's position has to be less than 100 mm, because of the technical timing performance.

– *Horizontal phase advance*

Between the injection septum (IS-1) and the injection kicker (KIK-3) (see fig. 1) has to be as close as

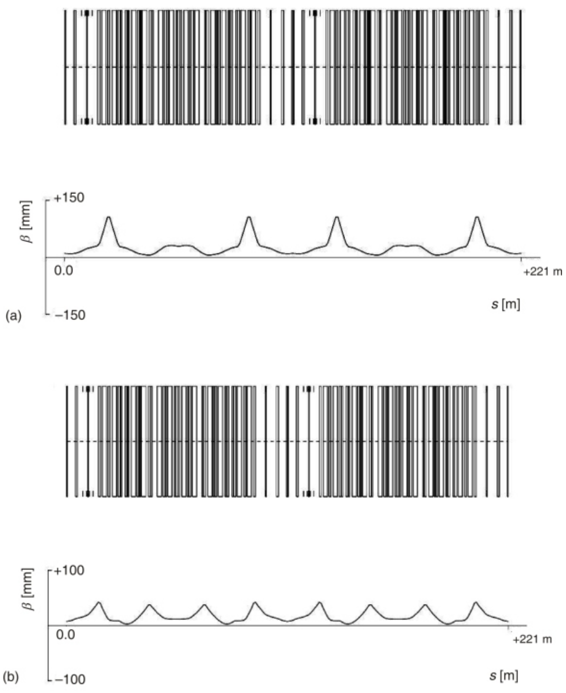

Figure 2. Calculated β functions (in millimeters) of the CR in horizontal (a) and vertical (b) plane as a function of the path length. The first optical element in this picture is quadrupole marked as Q-01 in fig. 1

possible to 90 °C for better deflection of the incoming beam to the central orbit of the ring.

The calculated β_B functions and the dispersion are shown in figs. 2 and 3. It is seen that the dispersion function has the double peak in the center of the arc, which is a result of the middle y-focusing quadrupole (Q-12) and two neighboring x-focusing quadrupoles (Q-10 and Q-11). Such dispersion shape leads to the isochronous setting with an available momentum acceptance of 0.6%. The beam sizes at the TOF deflector's position are ~35 mm and ~30 mm in the horizontal and vertical planes, respectively. The phase advance function between the injection septum and the injection kicker is about 70, which is acceptable for injection. The calculated betatron tunes in the CR are

$$Q_x \quad 35 \text{ and } Q_y \quad 2.00 \tag{12}$$

Second order calculation

The correction of the second-order contributions to the isochronicity can be done by installing the sextupole magnets in the ring at the place where the dispersion function has its maximum. The main term of the second-order to the isochronicity is $(t\ \delta\delta)$ and that term should be minimized.

Due to the fact that the quadrupoles in the arcs are not strong they do not create a strong natural chromaticity (ξ_{0x}, ξ_{0y} [6]. However, it still needs to be corrected. The correction of chromaticity is very important since it allows correcting the transverse contribution to time difference. It can be done by two sextupole families installed in the arcs of the ring where β functions are large. In the matrix formalism the chromaticity correction means that the following relations between the transport matrix elements must be fulfilled

$$(t|xx)x^2 \qquad (t|aa)a^2 \tag{13a}$$

$$(t|yy)\,y^2 \qquad (t|bb)b^2 \tag{13b}$$

At the same time the matrix term $(t\ \delta\delta)$ must be as lass as possible; theoretically speaking must be zero.

The first and the second order aberrations coefficient [6] of the ring is presented in tab. 1. From the marked number we can see that the isochronicity condition and chromaticity corrections are fulfilled in the second order of approximation.

The dependence of the revolution time on the momentum spread of the stored particles in the ring is shown in fig. 4. It can be seen that the isochronous condition is fulfilled in the first and the second-order of calculations.

The beam optics of the CR is shown in fig. 5.

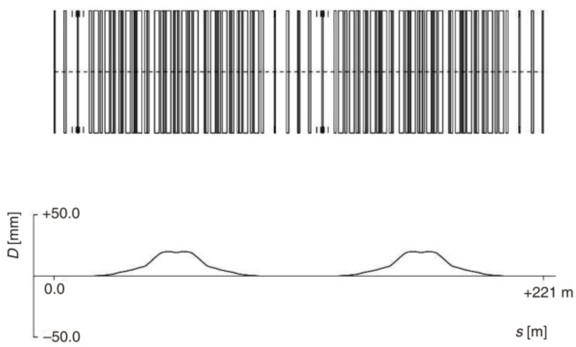

Figure 3. Calculated dispersion function (in millimeters) of the CR as a function of the path length. The first optical element in this picture is quadrupole marked as Q-01 in fig. 1

PLAN FOR THE FUTURE

Perspectives of further possible improvements are:

(1) taking into account the third-order of contribution to the revolution time. The third-order contribution can be corrected by installing the octopole families (Oct-1 and Oct-2) inside the two quadrupole families Q-09 and Q-11 by minimizing the main term $(t\ \delta\delta\ )$ of the third-order transfer matrix. The chromaticity correction also must be also considered in the third-order of calculations,
(2) effects of the fringe fields of quadrupoles,
(3) the magnetic field imperfections of the magnets on the mass resolving power, and
(4) influence of misalignments.

Table 1. The first and the second order aberration coefficients of the ring. X and Y are the horizontal and vertical displacement from the optic axis, A and B are the angle between paraxial ray and optic axis in horizontal and vertical planes, G and D are the mass and energy deviations of the particle from the reference particle, T is the time deviations of the particle from the reference particle at the same longitudinal positions

	X	A	Y	B	T
1 X	1.8426E-02	–2.5472E-03	0.0000E+00	0.0000E+00	–2.2665E-14
2 A	2.6395E-02	1.7782E-03	0.0000E+00	0.0000E+00	–1.1819E-14
3 Y	0.0000E+00	0.0000E+00	1.0618E-02	–3.3917E-03	0.0000E+00
4 B	0.0000E+00	0.0000E+00	2.4968E-02	1.4424E-03	0.0000E+00
5 G	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6 D	–1.0531E-12	–1.9488E-13	0.0000E+00	0.0000E+00	2.7217E-14
7 XX	–4.8654E-03	–6.9073E-05	0.0000E+00	0.0000E+00	–7.1129E-07
8 XA	5.8825E-03	–7.2041E-05	0.0000E+00	0.0000E+00	–2.0911E-06
9 XY	0.0000E+00	0.0000E+00	–1.2599E-04	4.4012E-05	0.0000E+00
10 XB	0.0000E+00	0.0000E+00	–1.7355E-04	1.7604E-04	0.0000E+00
11 XG	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
12 XD	2.7133E-06	–2.1744E-05	0.0000E+00	0.0000E+00	1.4323E-06
13 AA	1.5338E-03	–5.4749E-04	0.0000E+00	0.0000E+00	7.4845E-07
14 AY	0.0000E+00	0.0000E+00	1.6684E-03	2.2951E-05	0.0000E+00
15 AB	0.0000E+00	0.0000E+00	–9.0501E-05	–1.4376E-04	0.0000E+00
16 AG	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
17 AD	–2.2911E-04	2.6185E-07	0.0000E+00	0.0000E+00	7.4693E-07
18 YY	–5.3851E-04	7.5531E-05	0.0000E+00	0.0000E+00	–1.0420E-06
19 YB	6.7585E-04	–2.3931E-05	0.0000E+00	0.0000E+00	–2.6436E-06
20 YG	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
21 YD	0.0000E+00	0.0000E+00	–6.6318E-05	–3.3137E-05	0.0000E+00
22 BB	9.3177E-04	–2.7489E-06	0.0000E+00	0.0000E+00	8.2314E-07
23 BG	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
24 BD	0.0000E+00	0.0000E+00	–1.8753E-04	–9.0085E-06	0.0000E+00
25 GG	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
26 GD	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
27 DD	3.3274E-05	6.1578E-06	0.0000E+00	0.0000E+00	1.9582E-08

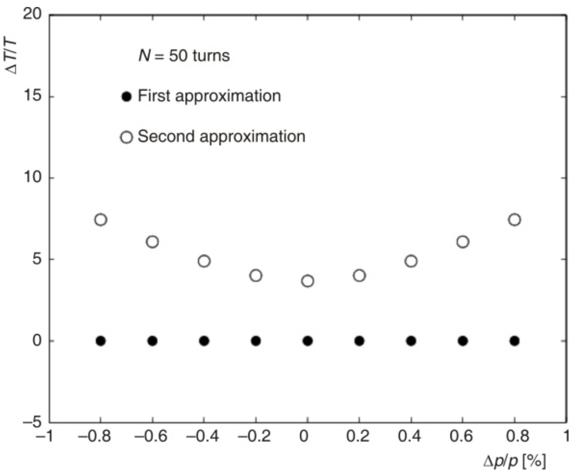

Figure 4. The revolution time relative deviation as a function of a momentum relative deviation

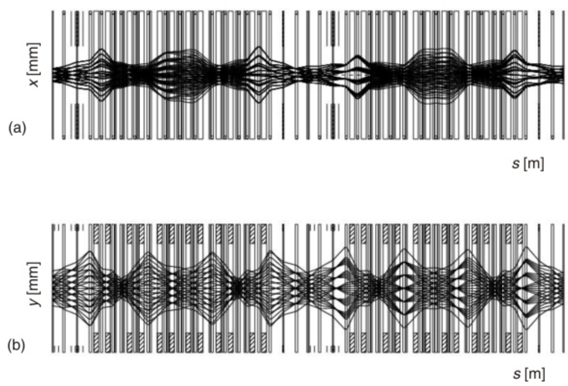

Figure 5. Beam optics of the CR in horizontal (a) and vertical (b) plane. The first optical element in this picture is quadrupole marked as Q-01 in fig. 1

CONCLUSIONS

Within this work the isochronous CR operational mode has been successfully developed and investigated. In this isochronous mode of operation heavy ions can be injected and stored in the CR ring fulfilling the isochronicity condition $\gamma \quad \gamma_t$. A mass resolving power of about $m/\Delta m$ = 150000 and a precision of $\delta m \; m \quad 0\cdot 10^{-6}$ are expected.

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ИЗОХРОНИ МОД РАДА БУДУЋЕГ КОЛЕКТОР РИНГА У ИНСТИТУТУ ЗА ТЕШКОЈОНСКА ИСТРАЖИВАЊА

У Институту за тешкојонска истраживања у Дармштату, Немачка, краткоживећа егзотична језгра производе се и издвајају у високоенергетском нуклеарном постројењу званом фрагмент сепаратор. Ова језгра убацују се и смештају у посебном прстену за одлагање који се зове експериментални прстен за одлагање. Кратко време њиховог полуживота ограничава примену досадашњих метода за мерење њихове масе у овим прстеновима (тренутно се у њима могу мерити масе нуклеона чије је време полуживота неколико секунди). У овом раду, развијен је и унапређен изохрони мод рада за будућу машину (колекторски прстен) која омогућава мерење масе језгара чија су времена полуживота реда величине неколико микросекунди. Очекује се да масена моћ раздвајања ове машине буде око 150000.

Кључне речи: егзотична језгра, полуживот, прстен за одлагање, колектор ринг